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# Picosecond Bunch length and Energy-z correlation measurements at SLAC's A-Line and End Station A.\*

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## Abstract

We report on measurements of picosecond bunch lengths and the energy-z correlation of the bunch with a high energy electron test beam to the A-line and End Station A (ESA) facilities at SLAC. The bunch length and the energy-z correlation of the bunch are measured at the end of the linac using a synchrotron light monitor diagnostic at a high dispersion point in the A-line and a transverse RF deflecting cavity at the end of the linac. Measurements of the bunch length in ESA were made using high frequency diodes (up to 100 GHz) and pyroelectric detectors at a ceramic gap in the beamline. Modelling of the beam's longitudinal phase space through the linac and A-line to ESA is done using the 2-dimensional tracking program LiTrack, and LiTrack simulation results are compared with data. High frequency diode and pyroelectric detectors are planned to be used as part of a bunch length feedback system for the LCLS FEL at SLAC. The LCLS also plans precise bunch length and energy-z correlation measurements using transverse RF deflecting cavities.

## INTRODUCTION

Control of the bunch length is important for accelerator operation, especially in the case of modern free electron lasers (FELs) such as the Linac Coherent Light Source (LCLS) at SLAC. In some cases, such as initial beam tune-up, an absolute measurement of the length of the bunch is needed, while in other situations, for example in the case of a feedback system, a relative measurement is satisfactory.

This paper addresses two different techniques recently tested at SLAC's End Station A (ESA) [1] to quantify the length of the bunch in that region of the machine. One technique is based on various measurements of the intensity of the radiation in specific frequency bands emitted from ceramic gaps in the beam pipe. The second method is based on a measurement of the longitudinal phase space of the beam emerging from the linac, and using the  $R_{56}$  of the subsequent bend to determine the phase space distribution in ESA.

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## BUNCH LENGTH IN ESA

As described in [1], bunches of  $\sim 2 \times 10^{10}$  electrons are accelerated to 28.5 GeV by the SLAC linac, and directed around a  $24.5^\circ$  bend known as the A-line, to bring the beam into ESA. Through control of the RF phase in the linac it is possible to tune the energy spread of the bunch, allowing for a range bunch lengths in ESA ( $\sim 300 \mu\text{m} - 1 \text{ mm}$ ).

## ABSOLUTE MEASUREMENT

The length of the bunch was measured by measuring the longitudinal phase-space at the end of the linac, and propagating this around the A-line bend using the known  $R_{56}$  value of 0.465 (see equation 1, where  $E$  is the design energy of the bunch,  $dE$  is the error in the energy of a particular particle,  $z_i$  is the longitudinal position of that particle,  $i = 1$  indicates the bunch before the bend, and  $i = 2$  indicates the bunch after the bend). Figure 1 shows the results from a LiTrack [2] simulation of the longitudinal profile at the end of the linac.

$$z_2 = z_1 + R_{56} \cdot \frac{dE}{E} \quad (1)$$

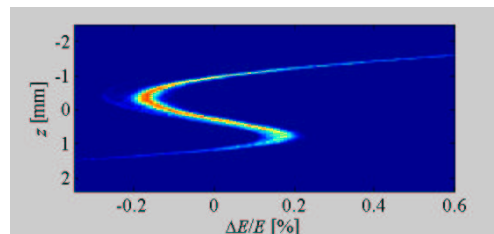


Figure 1: A simulation by LiTrack of the longitudinal phase space of the bunch at the end of the linac.

The synchrotron light generated by the passage of the bunch around the bend was captured with a CCD camera. Due to the non-zero dispersion of the A-line bend, the width of the synchrotron stripe is proportional to the energy spread of the particles in the bunch. The calibration of the synchrotron light monitor (SLM) is determined by varying the setpoint of the energy feedback and observing the horizontal position of the light spot.

The longitudinal profile was measured using a transverse deflecting cavity (LOLA) [3]. LOLA works by phasing the transverse mode of a cavity in such a way that the centre of

the bunch is at the zero crossing of the RF. This results in the particles within the bunch being given a transverse kick, whose amplitude is directly proportional (to first order) to the longitudinal position,  $z$ , within the bunch. The bunch may then be imaged on a screen in such a way that allows extraction of the bunch length.

For small changes of the phase of the LOLA RF, the vertical position of the image is directly proportional to the phase. As the frequency of the LOLA RF is known, a calibration of phase against vertical position on the screen gives a calibration of the position on the screen to the longitudinal position within the bunch.

The bunch's length, height, and tilt, contribute to the height of the digitised image. The bunch length is extracted by performing a parabolic fit to a plot of the height of the SLM image versus LOLA amplitude. Figure 2 shows an example of this calculation, where the offset from zero of the parabola's minimum is due to the transverse bunch size, and the plot's horizontal asymmetry indicates the presence of bunch tilt.

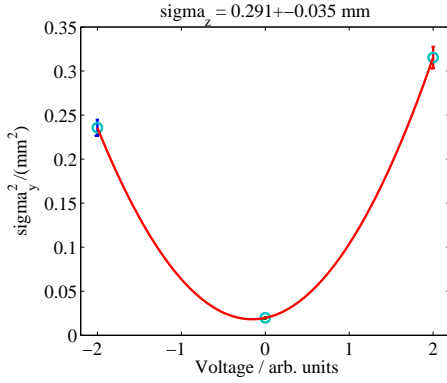


Figure 2: Parabolic fit of the standard deviation of the on-screen vertical projection to the LOLA amplitude (where negative amplitude implies a  $180^\circ$  change of phase).

By deflecting the bunch with LOLA at the end of the linac, the image formed on the SLM will be an expansion of the longitudinal phase space. Figure 3 shows the digitised image.

The digitised image was converted into an array of several thousand points in the longitudinal phase space with the same distribution as in the image. The ESA distribution was predicted from this using the  $R_{56}$  of the A-line. Measured bunch lengths at LOLA and ESA are shown in figure 4 for a range of linac phase settings, and a bunch charge of  $1 \times 10^{10} \text{ e}^-/\text{bunch}$ .

## RELATIVE MEASUREMENTS

Direct bunch length measurements in ESA are made using the same principle as that employed in the SLC Final Focus [5]. The beam radiates energy as it passes the electrical discontinuity presented by a ceramic gap, and this RF is captured by a waveguide, and channelled to a diode, which

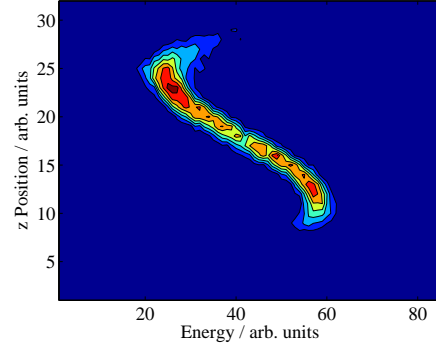


Figure 3: A digitisation of the SLM screen after being imported into Matlab.

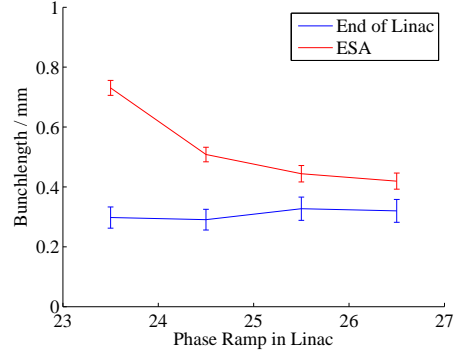


Figure 4: Bunch lengths measured at the end of the linac (at LOLA), and the predicted bunch length in ESA for a range of linac phase settings.

converts the RF power within a certain frequency range to a measurable voltage. Since the spectrum of the RF is dependent on the bunch length, the power in a frequency band is an indication of the bunch length. The frequency spectrum of a Gaussian charge distribution with rms length  $\sigma_z$  and total charge  $Q_b$ , moving at the speed of light, is,

$$I_b(\omega) = \frac{Q_b}{\sqrt{2\pi}} \cdot \exp\left(-\frac{\omega^2 \sigma_z^2}{2c^2}\right) \quad (2)$$

For the ESA tests, the ceramic gap radiation was monitored at 16 GHz, 23 GHz, and 100 GHz using suitable filters and diodes (two 100 GHz diodes were used, therefore, four diodes were tested in total). As can be seen in the photograph in figure 5, two waveguides (WR90 and WR10) were directed at a ceramic gap in ESA to couple the emission from the ceramic gap into the diodes. The  $\sim 20 \text{ m}$  long WR90 brought the signal out from the beamline enclosure, where it was lowpass filtered at 16 GHz for one channel, and 23 GHz for the other, and detected by diodes (Agilent 8470B). The diode's output was amplified and measured in a charge sensitive diode. The signal path to the 100 GHz diodes (millitech DXP-10) was very similar, however  $\sim 1 \text{ m}$  of WR10 waveguide was used instead of the WR90. No bandpass filter was necessary for the 100 GHz diodes due

to the strong high-pass nature of WR10 waveguide.

An additional bunch length measurement was made using a pyroelectric detector (Infratec LME-301) at a ceramic gap  $\sim 3$  m downstream of the gap used for the diode signals. Due to its wideband response, the pyro is sensitive to higher frequencies than the diodes, and so will be capable of measuring shorter bunches.

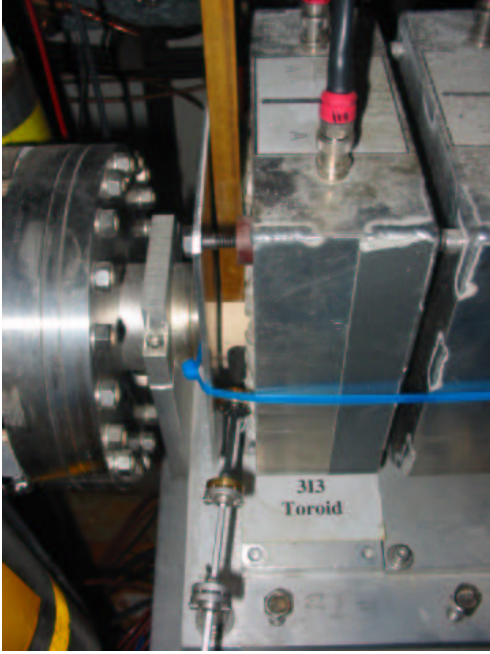


Figure 5: Photograph of the ceramic gap located at a toroid in ESA.

The bunch length in ESA was controlled with the linac RF phase, and the bunch length monitor (BLM) signals were recorded. The response of the 16 GHz and 23 GHz diodes were flat, implying no dependence on the bunch lengths measured. The 100 GHz and pyro-detector signals have been plotted in figure 6 after normalisation by the square of the bunch charge. It can be seen that the 100 GHz diodes have a very clear response. The pyro-detector has a similar response, however, it peaks at a higher linac phase due to its increased sensitivity range.

Figure 7 shows the normalised output of the 100 GHz diode during a phase ramp scan on the same scale as the bunch length data from figure 4. The sensitive range of the diode extends from a phase ramp of  $\leq 23^\circ$  to  $\sim 26^\circ$ , which, equates to a range of  $\geq 800 \mu\text{m}$  to  $\sim 400 \mu\text{m}$ . This fits well with expectations based on the theory presented in [5].

## CONCLUSIONS

It has been shown how bunch lengths of 1 mm to  $300 \mu\text{m}$  can be measured using a transverse cavity and a synchrotron light monitor in a dispersive region of a beamline. Once the longitudinal profile has been measured using this method, the optical model of the machine may be used to predict the phase space at other points in the beamline.

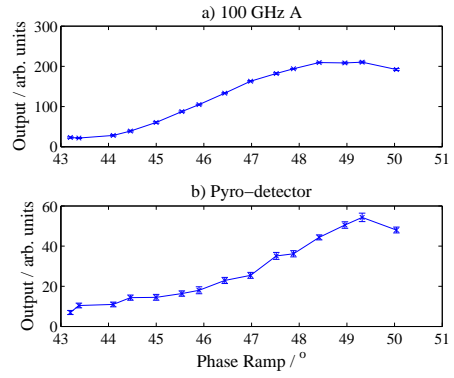


Figure 6: Normalised output of the 100 GHz diode and pyroelectric detectors at a range of phase ramp settings.

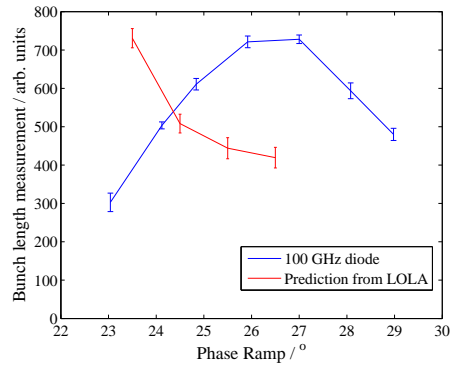


Figure 7: Normalised output of the 100 GHz diode during a phase ramp scan.

High frequency diodes and a pyro-detector were used in ESA to monitor the bunch length. The range of sensitivity of the diodes was calculated using the LOLA measurements, and matches well with theory.

## REFERENCES

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